Patent Application of

Keith DeConde, Srinivasan K. Ganapathi, Randy Gluck,

Steven Hovey, Shiva Prakash, and **Chris Stoessel**

for

Fingerprint Sensors using Membrane Switch Arrays

RELATED APPLICATION DATA

[0001]   This application is a continuation-in-part of U.S. Patent Application No. 09/571,765, filed 05/18/2000, entitled "Method and Apparatus for Pressure Sensing," which is herein incorporated by reference.

FIELD OF THE INVENTION

[0002]   The invention relates to biometric identification systems and methods, and in particular to fingerprint or skin texture identification systems and methods using switch arrays.

BACKGROUND OF THE INVENTION

[0003]   The fingerprint sensing industry uses several different conventional technologies to capture images of an individual's fingerprints.   Two prominent technologies are optical-based sensors and capacitance-based sensors.   In a typical optical sensor, a light source, lenses and a prism are used to image the ridges and valleys on a fingerprint, based on differences in the reflected light from the features.   Conventional capacitance sensors include two-dimensional array of capacitors defined on a silicon chip, and fabricated by semiconductor CMOS processing. The individual sensors on the chip form one plate of the parallel plate capacitor, while the finger itself, when placed on the array, acts as the second plate for the various localized sensors.   Upon contact with the array of sensors, the individual distance from each sensor to the corresponding point on the skin

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above the sensor is measured using capacitive techniques.   The
difference in distance to skin at the ridges and valleys of a
fingerprint identifies the fingerprint.

[0004]   Capacitive and optical sensors can be sensitive to oils
or grease on the finger and to the presence or absence of
moisture on the finger. In addition, the ambient temperature can
affect these sensors at the time of sensing. Under hot or cold
conditions, capacitive sensors can provide erroneous readings.
Finally, most sensors have abrasion resistant coatings.   The
thickness of the protective coating can affect the measurements.
The combined effect of these variables can result in distorted
fingerprint images.   Finally, in the case of silicon chip based
fingerprint sensors, the placement of the finger directly onto
the silicon increases the risk of electrostatic discharge and
damage to the sensor.

[0005]   Accordingly, there remains a need for a device suitable
for use as a texture image capture sensor that has high
sensitivity, yet can provide high lateral resolution. Moreover,
there further remains a need for a sensor that is suitable for
use in fingerprint image capture that is less sensitive to
adverse conditions such as extreme temperatures and skin oils and
grease.

SUMMARY OF THE INVENTION

[0006]   A texture sensor for sensing a texture having a
plurality of protrusions and a plurality of valleys, such as a
fingerprint or other skin texture, includes an array of membrane
switches disposed on a base. Each membrane switch comprises a
fixed electrode rigidly coupled to the base, and a flexible upper
membrane structures disposed over the base such that a cavity
separates a central region of the membrane structure and the

base.   The membrane structure comprises a movable electrode disposed facing the fixed electrode. Disposing a protrusion of the texture over the membrane switch causes a flexure of the membrane resulting in a change in contact state between the fixed electrode and the movable electrode.   Disposing a valley of the texture over the membrane switch does not result in the change in contact state between the fixed electrode and the movable electrode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007]   The foregoing aspects and advantages of the present invention will become better understood upon reading the following detailed description and upon reference to the drawings where:

[0008]   Figs. **1-A** and **1-B** are schematic diagrams of a switch array forming part of a sensing circuit according to the preferred embodiment of the present invention.

[0009]   Fig. **2**   shows an isometric view of four adjacent membrane switches according to the preferred embodiment of the present invention.

[0010]   Figs. **3-A** and **3-B** show isometric and side sectional views, respectively, of a membrane switch according to the preferred embodiment of the present invention.

[0011]   Figs. **4-A**, **4-B**, and **4-C** show isometric, top, and side sectional views, respectively, of the structure resulting after a lower electrode is formed on a sensor substrate, according to the preferred embodiment of the present invention.

[0012]   Figs. **5-A**, **5-B**, and **5-C** show isometric, top, and side sectional views, respectively, of the structure resulting after

the formation of a pair of sacrificial layers above the lower electrode, according to the preferred embodiment of the present invention.

[0013]   Figs. 6-A, 6-B, and 6-C show isometric, top, and side sectional views, respectively, of the structure resulting after an upper electrode membrane is formed above the sacrificial layers, according to the preferred embodiment of the present invention.

[0014]   Figs. 7-A and 7-B illustrate, in top and side sectional views, respectively, the formation of a protective field oxide over the structure of Figs. 6-A through 6-C, according to the preferred embodiment of the present invention.

[0015]   Figs. 8-A and 8-B illustrate, in top and side sectional views, respectively, the formation of a polymer diaphragm and vent seals on the structure of Figs. 7-A, 7-B, according to the preferred embodiment of the present invention.

[0016]   Figs. 9-A through 9-C show side sectional views of three membrane switches according to alternative embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0017]   In the following description, it is understood that each recited element or structure can be formed by or be part of a monolithic structure, or be formed from multiple distinct structures. Unless otherwise specifically stated, the statement that a first layer or structure is disposed or deposited on a second layer or structure is understood to allow for the presence of parts of the first or second layer or structure that are not so disposed or deposited, and further allow for the presence of intermediate layers or structures between the first and second

layers or structures. The terms "chip base" and "chip substrate" are understood to encompass monolithic substrates as well as structures containing multiple layers or parts. The terms "upper" and "lower" are used to describe relative positions, and do not necessarily refer to the direction of gravity during operation of the sensor. A set of elements is understood to include one or more elements. A plurality of elements is understood to include two or more elements. Any recitation of an element is understood to refer to at least one element.

[0018]   The following description illustrates embodiments of the invention by way of example and not necessarily by way of limitation.

[0019]   Figs. **1-A** and **1-B** are schematic diagrams illustrating the electrical connections of a fingerprint or texture sensor **20** according to the preferred embodiment of the present invention. Sensor **20** comprises an array of switches (cells) spaced from each other by an appropriate distance that is a fraction of the inter-ridge spacing of the fingerprint or skin texture to be sensed. The preferable range of this fraction is 1/2 to 1/20. Typical spacings between fingerprint ridges are 400-500 μm. Each switch corresponds to an intersection of a row line and a column line illustrated in Figs. **1-A** and **1-B**. Closed switches are denoted by their associated resistances R_s.   The 8 x 8 switch array illustrated in Figs. **1-A** and **1-B** is part of a larger m x n array.

[0020]   A plurality of metallic leads arranged in an m x n orthogonal grid and electrically isolated from each other serve as the electrical input and output lines for each switch. The orthogonal grid of metallic leads comprises conductive rows **22** and columns **24**, which lead into and out of each switch. Each row/column combination of conducting leads corresponds uniquely

to a specific switch in the array. Each switch is addressed by applying a voltage and sensing a current between the row and column leads corresponding to the switch.

[0021]   Each column lead **24** is connected to an input of a column multiplexer **30**, while each row lead **22** is connected to an input of a row (downstream) multiplexer **32**. Column multiplexer **30** and row multiplexer **32** are used to individually address each of the switches in the matrix, and thereby determine the state (open or closed) of each switch. Such multiplexers and the manner of causing the addressing of each switch are known, and thus a detailed description thereof is not necessary for an understanding of the present invention.

[0022]   Each switch includes a lower conductive electrode, and a membrane structure including an upper electrode disposed over the lower electrode. The lower electrode of each switch is electrically connected to a column (or row) lead, and the upper conducting electrode is electrically connected to a row (or column) lead. Since the row and column conductor leads are electrically isolated from each other, the switch is electrically open in the quiescent state, and no current passes between the row and the column corresponding to the switch.

[0023]   When a fingerprint is placed on the sensor, the upper electrodes of certain switches are pressed downward by the ridges of the fingerprint, while the upper electrodes of the other switches are not sufficiently deflected to close the switches. With appropriate design and fabrication of the switches, the upper electrodes deflect downward and establish contact with the corresponding lower electrodes when a ridge of a fingerprint is applied to the switches. The upper electrodes then revert to their original positions when the ridge of the fingerprint is

removed.   If a switch in the array resides directly beneath a ridge of the fingerprint, it is deflected and the switch is closed.   If a switch resides beneath a valley of the fingerprint, then it is not deflected and it remains open.   When closed, a switch establishes electrical contact between the row and column corresponding to that switch.   In this way, one can generate a map of the contact points or the ridges on the fingerprint, and get an accurate reproduction of the fingerprint.

[0024]   An electrical circuit such as a conventional counter, shift register and operational amplifier attached to a multiplexer, combined with voltage sources and current/voltage detectors can be used to detect the output current or voltage from the row/column being addressed.   The magnitude of the output current indicates whether a particular switch is closed or open. Each switch can be polled individually using the multiplexer and simple controlling electronics and software to acquire a map of the closed switches.   The switch map represents a map of the fingerprint image, since the image is a reproduction of the ridges on the fingerprint.

[0025]   A large resistive device is preferably placed in series with each switch in the array so that one can easily distinguish between the open and closed states of the switch when the switch is polled.   The resistive device is preferably a passive resistor with a resistance of 5,000 Ω to 500,000 Ω.   Other suitable resistive devices include active devices such as p-n diodes with low forward resistance and low leakage current characteristics, field effect transistors, thin film transistors, and other types of transistors with similar characteristics.   A pull-down resistor R_p is connected between ground and each input of downstream multiplexer **32**. Pull-down resistor R_p is preferably a passive resistor with a resistance of approximately 50-250 Ω.

Pull-down resistor R_p and the resistor placed in series with each switch facilitate the reliable detection of the state (open/closed) of each switch. Ascertaining the state of the switch relies on detecting a significant difference in the voltages (or currents) measured for the closed and open states of the switch.

[0026]   Consider a source of constant current, sourcing from the column multiplexer **30** and sinking through the row or downstream multiplexer **32**.   Fig. **1-A** illustrates the current paths through sensor **20** as column E and row 4 are addressed. Addressing column E and row 4 is used to determine the state of the switch E4. The current that passes down the addressed column E encounters a parallel network of closed and open switches. Each of rows 2, 4, 6, and 7 contains a closed switch along column E.   Only the closed switches provide current paths through the sensor, since the open switches provide essentially infinite impedance.   The pull-down resistors R_p at the inputs of the row multiplexer **32** are selected such that each closed switch on the addressed column, including the switch on the addressed row, presents approximately the same resistance to the current.

[0027]   The current passing through column E is split evenly between all the closed switches R_s along column E, in this case the closed switches R_s on rows 2, 4, 6, and 7.   If there are n closed switches on the addressed column, then the current that flows through the switch being addressed can be approximated by I/n, where I is the total source current. Some of the current that makes its way to the addressed row is lost when it shunts back out through the closed switches on the addressed row. However, by making the switch resistance adequately high, this shunting can be reduced to a small fraction of the current that sinks through row multiplexer **32**.   Additionally, some of the

current distributed throughout the fingerprint array does not sink through the various row pull-downs and makes its way back to the addressed row, increasing the current detected by the circuit.

5 [0028]   Fig. **1-B** illustrates the current paths through sensor **20** as column E and row 5 are addressed. Row 5 does not share any of the initial current that is split between the closed switches R_s on rows 2, 4, 6, and 7 on the addressed column E. The only current in the addressed row 5 is a portion of the

10 current that does not sink through the various pull-down resistors R_p on the rows 2, 4, 6, and 7 with closed switches R_s on the addressed column E.

[0029]   The ratio of currents through the row multiplexer **32** for a closed versus an open switch can be considered to be the

15 quality factor for detecting the state of any switch in the array. An equation that approximates this ratio is:

$$I_{closed}/I_{open} = 1 + NX/n(1 - X), \qquad [1]$$

wherein $X = (R_{sw}/n + R_{sw}/n^2 + R_{pd}/n^2)/(R_{pd} + R_{sw}/n + R_{sw}/n^2 + R_{pd}/n^2)$,
R_{sw} = Resistance in series with each switch,

20 R_{pd} = Pull-down resistance at inputs to the row multiplexer,
N = Total number of switches in any given row or column,
n = Average number of closed switches on any given row or column.

[0030]   Some typical values for the parameters in the above equations are:

25 R_{sw} = 100,000 Ω
R_{pd} = 100 Ω
N = 256 Switches
n = 128 Switches
X = .887

which yields a current ratio or quality factor of $I_{closed}/I_{open} = 16.7$, a ratio that is large enough to provide resolution in distinguishing between a closed and an open switch.

[0031]   In accordance with an aspect of a method of fingerprint identification/verification in accordance with the invention, before fingerprint measurements are performed, the quiescent impedance of each switch is measured in order to determine whether there is a stress on a particular switch. Measuring the quiescent impedance of each switch with no finger on the sensor provides a baseline measurement value for the switch. The baseline can be established either immediately prior to or immediately following the imaging of the fingerprint. The impedance measurement for each switch is repeated with the finger on the sensor, and the switches that have changed state from electrically open to electrically closed are recorded. The state-change information is mapped for the entire switch array to obtain an image of the fingerprint.

[0032]   Comparing fingerprint measurements to the baseline allows a reduction of the effect of ambient temperature, humidity, and stress on the measurements. The baseline comparison also reduces the effect of individual bad sensors that are electrically closed prior to the application of the fingertip. Some switches may be closed or may appear to be closed in the absence of applied pressure, due to processing errors or undue deflection of some membranes.

[0033]   Fig. 2 shows an isometric view of four adjacent switches **40** forming part of sensor **20**, according to the preferred embodiment of the present invention. As illustrated, switches **40** are disposed in a cartesian array along a planar surface, and are electrically interconnected by row leads **44** and column leads **46**. The interiors of the switches **40** disposed along each row are

interconnected through tunnels **48**, such that the interior chambers of the switches **40** disposed along each row define a common space. Tunnels **48** provide pathways for equalizing the pressures within the chambers of different switches **40**. Such pressure differences can affect the force required to close different switches **40**.

[0034]   Figs. **3-A** and **3-B** show isometric and side sectional views, respectively, of a membrane switch **40** according to the preferred embodiment of the present invention. Switch **40** is shown in its quiescent, unflexed state. Fig. **3-B** corresponds to the section AA' illustrated in Fig. **3-A**. Referring to Fig. **3-B**, switch **40** is formed on a base comprising a substrate **62** and an insulating layer **64** extending over substrate **62**. A conductive, planar lower electrode **50** is disposed over insulating layer **64**. A flexible membrane structure **52** is disposed over lower electrode **50** and is separated from lower electrode **50** by a chamber or gap **54**. Preferably, gap **54** is filled with air and is capable of pressure equalization with the outside atmosphere. The edges of membrane structure **52** are anchored to the stationary part of switch **40** and remain fixed, while the center of membrane structure **52** is capable of downward deflection in response to the application of downward pressure by a fingerprint ridge.

[0035]   Membrane structure **52** includes a conductive, creased upper electrode **66** disposed facing lower electrode **50**, and a diaphragm or button **68** stacked above upper electrode **66**. Diaphragm **68** forms the top, external boundary of switch **40**. The fingerprint or texture of interest is pressed directly on diaphragm **68**. Diaphragm **68** provides added thickness, mechanical stability, and impact resistance to membrane structure **52**.

Preferably, the height of the top surface of diaphragm **68** is within less than +4 µm, in particular within -0.5 µm or less, of the height of the rigid area surrounding diaphragm **68**. Excessively increasing the height of membrane structure **52** can make switch **40** vulnerable to external shocks. Excessively lowering the height of membrane structure **52** relative to its fixed surroundings can impede the protrusion of texture ridges to positions needed for establishing effective contact with the upper surface of membrane structure **52**. The height of the top surface of diaphragm **68** can exceed the height of the surrounding rigid area by a few microns if improved sensitivity is desired. Preferably, the height of the top surface of diaphragm **68** is not below the height of the surrounding rigid area by more than 0.25 to 0.5 µm, if at all.

[0036]   Upper electrode **66** is disposed along the bottom of membrane structure **52**. Upper electrode **66** includes a planar contact surface facing lower electrode **50**, such that downward flexing of membrane structure **52** establishes electrical contact between the contact surfaces of upper and lower electrodes **50**, **66**. For clarity, upper electrode **66** and lower electrode **50** are hatched in Fig. **3-B**.

[0037]   Lower electrode **50** is electrically connected to row lead **44** through a passive resistor **70** disposed over insulating layer **64**. In general, lower electrode **50** may also form part of row lead **44**. Upper electrode **66** is electrically connected to column lead **46** (shown in Fig. **3-A**) through a conductor which forms part of the cover of tunnel **48** extending between chamber **54** and column lead **46**, as will be further illustrated below.

[0038]   Row and column leads **44, 46** are made of a highly conductive material that can be easily patterned using known photolithography and etching techniques.   Leads **44, 46** are electrically isolated from each other and from all other structures by films of insulating material.   Lower and upper electrodes **50, 66** are preferably made of a material that is resistant to corrosion and oxidation, has a relatively high conductivity or forms an oxide having high conductivity, and is amenable to patterning by existing processes.   Gold, copper, chromium, molybdenum, ruthenium, and indium tin oxide (ITO) are examples of preferred materials for lower and upper electrodes **50, 66**.

[0039]   Diaphragm **68** is made of a material which is resistant to corrosion and oxidation, which can be made to adhere well to upper electrode **66**, and which has a desired stiffness. Diaphragm **68** is preferably made of a plastic or polymer. In a present implementation, diaphragm **68** is made of Shin-Etsu SINR 3180, a silicone-based polymer having a Young's modulus of about 40 MPa. Other suitable materials for diaphragm **68** include aluminum oxide, silicon dioxide, silicon nitride, metallic films, and polymer films such as elastomers, polyacrylates, etc. The choice of materials for diaphragm **68** and/or upper electrode **66** affects the flexibility and reliability of membrane structure **52**. The materials and dimensions of diaphragm **68** and upper electrode **66** are preferably chosen such that the performance of membrane structure **52** does not degrade due to repeated deflections over the lifetimes of switch **40**. Moreover, the materials and dimensions of membrane structure are chosen such that membrane structure fully deflects under typical pressures applied by fingerprints, but does not substantially deflect in the absence of applied fingerprint pressures.

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[0040]   Typically, the load applied by an individual's finger on a sensor is in the range of 100-500 grams. The fingerprint is approximately 15 mm X 15 mm in general diameter. Thus, an array of switches with total dimensions of 15 mm X 15 mm is generally appropriate for sensing fingerprints. The spacing between typical fingerprint ridges is on the order of 400 μm. If the switches are assumed to be placed 50 μm apart on a two dimensional x-y grid, an array of on the order of 300 X 300 switches would be suitable for covering a sensor surface area of 15 mm X 15 mm. There are a total of 90,000 sensors in such an array, and the applied load from the fingertip can be assumed to be distributed over these 90,000 sensors. As a first order approximation, one can assume that the area of the ridges is equal to that of the valleys. Thus, approximately 45,000 sensors bear the applied load. If one conservatively assumes an applied load of 90 grams from the fingerprint, then each cell bears an approximate load of about 2 mg.

[0041]   Membrane structure 52 is preferably designed such that it deflects adequately under the application of 2 mg of load to establish contact between upper electrode 66 and lower electrode 50, and then reverts to its original, quiescent position when the load is removed. The geometry and material properties of membrane structure 52 can be empirically tailored so membrane structure 52 causes closure of its corresponding switch if membrane structure 52 is positioned under a ridge or protrusion of the texture of interest, and does not cause such closure if membrane structure 52 is positioned under a valley or depression of the texture of interest.

[0042]   An order-of-magnitude estimate of the dependence of the central deflection of a circular membrane on the properties of

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the membrane can be calculated by considering an ideal, flat disk-shaped monolithic membrane anchored around its circular edge. The central deflection of such a membrane is on the order of

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$$y = \frac{Pha^4}{EA_p h^4} \qquad [2]$$

where P is applied pressure,

h is the membrane thickness,

a is the membrane radius,

10 E is Young's Modulus for the membrane material,

and A_p is a dimensionless stiffness coefficient.

Equation [2] applies to both flat and corrugated diaphragms. For a flat diaphragm and a Poisson ratio μ = 0.30, the value of A_p is 5.86. The value of A_p is higher for corrugated membranes.

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[0043]   Consider some approximate values for the variables in Eq. [2]:

P = 3 x 10^4 Pa;

E = 3 x 10^{11} Pa;

20 a = 1.6 x 10^{-5} m (16 μm);

h = 1.5 x 10^{-7} m (0.15 μm);

A_p = 6.

The value of P above corresponds approximately to 5 psi, or a

25 load of about 2 mg applied over a circle having a radius of about 16 μm. The value of E above is on the order of the Young's moduli of metals such as Cr (2.8 x 10^{11} Pa) and Mo (3.24 x 10^{11} Pa). The values above yield a central deflection of about 3 x 10^{-7} m, or about 0.3 μm. Actual deflection values will

30 depend on the particular materials, dimensions, and geometries (e.g. corrugation) employed in a given switch. Furthermore, the

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deflection of membranes comprising multiple stacked layers will depend on the properties of those layers. Eq. [2] nevertheless provides a useful indication of the effect of several variables on the deflection of the upper membrane in response to applied force.

[0044]   If the quiescent state separation of the upper and lower electrode is made to be slightly smaller than the typical deflection of the membrane in response to an applied fingerprint ridge, the upper electrode makes contact with the lower electrode under applied pressure, allowing detection of the fingerprint ridge. The separation between the upper electrode and the lower electrode is preferably larger than any height or thickness variability that might arise in the membrane due to processing induced stresses, such that such stresses do not result in closure of the switch in the absence of applied pressure.

[0045]   The fabrication of switches 40 will be described with reference to Figs. 4-A through 8-B. The description below will focus on a single switch 40. As is apparent to the skilled artisan, structures corresponding to multiple switches 40 are formed in each step described below. The various deposition/patterning steps can be performed using known processes such as dry etching, wet chemical etching, and deposition using photolithographic liftoff stencils.

[0046]   Figs. 4-A, 4-B, and 4-C show isometric, top, and side sectional views, respectively, of the structure resulting after lower electrode 50 is formed along the base of a switch 40, according to the preferred embodiment of the present invention. The view of Fig. 4-C is taken along the line AA' shown in Fig. 3-A. The fabrication process starts with the base formed by substrate 62 and insulating layer 64. Preferred materials for

substrate **62** include silicon, aluminum oxide, and glass. Preferred materials for insulating layer **64** include silicon dioxide, silicon oxinitride, and aluminum oxide. Alternative materials for substrate **62** include insulators such as plastics. Insulating layer **64** can be formed on substrate **62** by sputtering or other known methods. In a present implementation, substrate **62** is made of silicon or glass while insulating layer **64** is made of silicon dioxide.

[0047]   Referring back to Figs. **4-A**, **4-B**, and **4-C**, a passive resistor strip **70** is deposited onto insulating layer **64** and patterned using dry etching, wet etching, or using a photolithographic liftoff stencil during deposition. Alternatively, resistor strip **70** can be electroplated in the required pattern. Resistor strip **70** is preferably made of a high-resistivity material such as tantalum oxide, titanium dioxide, doped silicon, or another oxidized metal or doped semiconductor. The thickness of resistor strip **70** is preferably between 200 Å and 5000 Å. The thickness, length, width, and composition of resistor strip **70** are chosen so as to yield a desired resistance value. In a present implementation, resistor strip **70** consists of a 2500 Å-thick layer of tantalum oxide, having a resistance of approximately 100,000 Ω.

[0048]   A straight conductive row lead **44** is formed on insulating layer **64**. Row lead **44** is preferably made of highly-conductive material(s) such as Cu, Cr, Au, Mo, and ITO. The thickness of row lead **44** is preferably between 1000 and 5000 Å, in particular between 2000 and 4000 Å. In a present implementation, row lead **44** is formed by a 300 Å Cr/2500 Å Cu/1000 Å Cr stack.

[0049]   Lower electrode **50** is deposited onto insulating layer **64**, for example using a photolithographic liftoff stencil. Lower electrode **50** has a substantially planar upper contact surface for establishing electrical contact with the upper electrode of the switch. The top surface of lower electrode **50** is preferably formed of metal(s) or alloy(s) that are resistant to corrosion, abrasion, frictional forces, and etchant materials used in subsequent processing steps, as described below. Preferred materials for lower electrode **50** include Cr, Au, Ru, Mo, and ITO. The thickness of lower electrode **50** is preferably between 500 and 5000 Å, in particular between 1000 and 2000 Å. In a present implementation, lower electrode **50** is formed by a 100 Å Cr/500 Å Au/300 Å Ru stack.

[0050]   Figs. **5-A**, **5-B**, and **5-C** show isometric, top, and side sectional views, respectively, of the structure resulting after several additional fabrication steps performed according to the preferred embodiment of the present invention. An insulator layer **80** is deposited along the entire surface of the structure shown in Figs. **4-A**, **4-B**, and **4-C**, except for the middle part of lower electrode **50**. The uncovered middle part of lower electrode **50** is to form the contact surface of the switch. Insulator layer **80** serves to insulate row lead **44**, resistor **70**, and lower electrode **50** from conductive structures which are to be subsequently deposited. Insulator layer **80** extends over the edge of lower electrode **50**, and forms an annular protrusion **81** around the edge of lower electrode **50**. Annular protrusion **81** serves to generate an annular crease in subsequently deposited layers, including the upper electrode of switch **40**. Preferred materials for insulator layer **80** include alumina, silicon oxide, and silicon oxynitride. In alternative implementations, insulator

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layer **80** can be formed by a plastic or polyimide. The thickness of insulator layer **80** is preferably between 500 Å to 1 μm. In a present implementation, insulator layer **80** is formed by a 5000 Å-thick alumina layer.

[0051]   A straight column lead **46** is deposited over insulator layer **80**, away from lower insulator **50** and along a direction perpendicular to the direction of row lead **44**. Suitable materials and thicknesses for column lead **46** are generally similar to those described above for row lead **44**. In a present implementation, column lead **46** is formed by a 100 Å Cr/4000 Å Au/300 Å Cr stack.

[0052]   A first sacrificial layer **82** is formed over the contact surface of lower electrode **50**, and over part of insulator layer **80** and column lead **46**. Sacrificial layer **82** includes a generally circular central part **86** extending over the entire extent of the contact surface of lower electrode **50** and over a part of insulator layer **80** surrounding the contact surface. Central part **86** of sacrificial layer **82** will form part of the air chamber of switch **40**, between lower electrode **50** and the upper electrode. Sacrificial layer **82** also includes a tunnel part **90a-b**, which extends away from central part **86** in a direction parallel to row lead **44**. Tunnel part **90a-b** will form an inter-cell air tunnel for facilitating the equalization of pressure between different switch chambers. Sacrificial layer **82** further includes a set of four vent extensions **88** extending away from central part **86**, at 45^0 relative to row lead **44** and column lead **46**. Vent extensions **88** serve to provide access to sacrificial layer **82** during a subsequent step in which

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sacrificial layer **82** is removed. In general, one or more (e.g. more than four) vent extensions may be used.

[0053]   The thickness of sacrificial layer **82** defines the spacing between the contact surfaces of lower electrode **50** and the upper electrode to be subsequently deposited over sacrifical layer **82**. The thickness of sacrificial layer **82** is preferably between 500 Å and 1 µm, in particular between 0.1 and 0.5 µm. Suitable materials for sacrificial layer **82** include Cu, Al, or any other etchable materials. In a present implementation, sacrificial layer **82** is formed by 2000 Å-thick Cu. In alternative embodidiments, the sacrificial layer may include an organic release material such as a polyimide.

[0054]   A second, annular sacrificial layer **84** is deposited onto first sacrificial layer **82**, along an annular portion flanking the contact surface of lower electrode **50** and extending generally over the annular protrusion **81**. Sacrificial layer **84** serves to provide additional annular creasing to the upper electrode to be subsequently deposited, in order to reduce residual stresses in the upper electrode. Suitable thicknesses and materials for second sacrificial layer **84** are similar to those described above for first sacrificial layer **82**. In a present implementation, second sacrificial layer **84** is formed by 3000 Å-thick Cu.

[0055]   Figs. **6-A**, **6-B**, and **6-C** show isometric, top, and side sectional views, respectively, of the structure resulting after an upper electrode **66** is formed above sacrificial layers **82**, **84**, according to the preferred embodiment of the present invention. Upper electrode **66** is deposited over the entire extents of sacrificial layers **82**, **84**, as well as over insulator layer **80** and

column lead **46**. As is clear to the skilled artisan, upper electrode **66** extends over only parts of insulator layer **80** and column lead **46**. Upper electrode **66** includes a central part **92** extending above lower electrode **50** and sacrificial layers **82, 84**,

5   an edge anchor part **94** extending over insulator layer **80** but not over sacrificial layers **82, 84**, and a tunnel and column contact part **96** extending over column lead **46**. Upper electrode **66** does not extend over the tips of the vent extensions **88** defined by sacrificial layer **82**, in order to provide access to sacrificial

10 layers **82, 84** through the vent extensions during subsequent steps in which sacrificial layers **82, 84** are removed.

[0056]   Edge anchor part **92** anchors the edges of upper electrode **66** to the fixed insulator layer **80**. Central part **92** is designed to be capable of downward flexing motion after the

15 removal of sacrificial layers **82, 84**. Central part **92** includes annular creases for decreasing stresses within upper electrode **66**. Central part **92** further includes a planar inner contact surface facing the contact surface of lower electrode **50**. Tunnel and column contact part **96** defines the electrical contact

20 between column lead **46** and upper electrode **66**, as well as the top part of the intercell tunnel extending over column lead **46**.

[0057]   Preferred materials for upper electrode **66** include Au, Cr, Mo, Ru, and ITO. The thickness of upper electrode **66** is chosen so as to produce desired stiffness and stress

25 characteristics. Preferably, the thickness of upper electrode **66** is between 800 and 4000 Å, in particular between 1000 and 2000 Å. In a present implementation, upper electrode **66** is formed by a 500 Å Au/1000 Å Cr stack, with the gold layer stacked below the chromium layer. The free part of upper electrode **66** preferably

has an overall size or diameter between 1 and 5 μm. In a present implementation, the diameter of the free part of upper electrode 66 is about 3.2 μm.

[0058]   Figs. 7-A and 7-B illustrate, in top and side sectional views, respectively, the formation of a field oxide insulator and impact-absorbing support 100 over the structure of Figs. 6-A through 6-C, according to the preferred embodiment of the present invention. Support 100 is deposited over the entire extent of the underlying structure, except over the center of upper electrode 66 and over the tips of vent extensions 88. Support 100 can extend over the anchor part 94 of upper electrode 66. Support 100 does not extend over the central part of upper electrode 66, in order to allow the flexure of upper electrode 66. Support 100 does not extend over the tips of vent extensions 88, in order to provide vents for removing the sacrificial layers from switch 40. Support 100 serves to electrically insulate column lead 46 and upper electrode 66 from the external environment. Support 100 also provides a robust external surface for switch 40 outside the area defined by the flexible membrane structure that drives the motion of upper electrode 66. The robust external surface provided by support 100 is capable of absorbing external shocks and hits to the switches 40, minimizing the damage to the flexible membrane structures of switches 40. Such hits can occur during normal operation of a fingerprint sensor, for example if a user bumps or drops an object onto the surface of the sensor.

[0059]   Preferred materials for support and insulator layer 100 include silicon dioxide, silicon nitride, and silicon oxynitride. The thickness of layer 100 is preferably between 1000 Å and 3 μm.

In a present implementation, layer **100** is formed by 0.75 μm-thick field silicon dioxide.

[0060]   After layer **100** is formed, a wet chemical etch is used to remove the sacrificial layers present between lower electrode **50** and upper electrode **66**. The sacrificial layers are removed through the vents defined over the tips of vent extensions **88**. Following the removal of the sacrificial layers, lower and upper electrodes **50**, **66** are separated by the air gap or chamber **54**.

[0061]   Figs. **8-A** and **8-B** illustrate, in top and side sectional views, respectively, the formation of a flexible top diaphragm **68** and vent seals **102** on the structure of Figs. **7-A**, **7-B**, according to the preferred embodiment of the present invention. Diaphragm **68** is formed over upper electrode **66** and over the inner edge of layer **100**.   Together with upper electrode **66**, diaphragm **68** forms a flexible membrane structure **52** capable of flexing to establish contact between upper electrode **66** and lower electrode **50**.   Diaphragm **68** adds thickness and stiffness to membrane structure **52**.   Anchoring the external edge of diaphragm **68** to layer **100** reduces the stresses caused within upper electrode **66** by diaphragm **68**.

[0062]   Preferably, the height of membrane structure **52** is approximately equal to the height of the support layer **100**. It is preferred that the top surface of membrane structure **52** be within less than 4 μm higher and 0.5 μm lower than the top surface of support layer **100**. If the top surface of membrane structure **52** is too low relative to support layer **100**, support layer **100** can obstruct the penetration of fingerprint ridges to membrane structure **52** and thus prevent the closing of switch **40**.

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If the top surface of membrane structure **52** is too high relative to support layer **100**, switch **40** can become unnecessarily vulnerable to external impact forces capable of stressing or damaging membrane structure **52** or lower electrode **50**.

[0063]   A set of four vent seals **102** are deposited over the sacrificial layer vents defined in support layer **100**, for closing the internal chamber of switch **40** to outside particles that could otherwise contaminate switch **40**.   Vent seals **102** preferably are not air-tight, such that the air pressure within the internal chamber of switch **40** can equalize with the air pressure in the external environment of switch **40**.   Preferred materials for vent seals **102** include silixon oxide, silicon nitride, metals, or other materials that will not leak into the internal chamber of switch **40**.   The thickness of vent seals **102** is preferably sufficiently high so that vent seals **102** cover the aperture left behind by the vent extensions of the sacrificial layers, but not so high that vent seals **102** interfere with the sensing of fingerprints by blocking access to the membrane structure **52**.   In a present implementation, vent seals **102** include a lower layer of 0.6 µm-thick silicon dioxide, and a polymer cap stacked over the silicon dioxide lower layer.   In this implementation, it was observed that the air pressure within the internal switch chamber substantially equalizes with the atmospheric air pressure outside of the switch within a time period on the order of half an hour or less.   In alternative implementations, suitable vent seals may be formed by a single layer of a material such as silicon nitride or a metal.

[0064]   Fig. 9-A shows a side sectional view of a membrane switch **240** according to an alternative embodiment of the present invention.   Switch **240** is shown in its quiescent, open state.

Switch **240** is part of a larger two-dimensional array, and is connected to row and column leads (not shown) as described above. Switch **240** includes a membrane structure (membrane) **252** comprising an upper electrode **266**. Upper electrode **266** is attached to the underside of a flexible, insulative, protective flat membrane **268**. Membrane **268** is anchored around its edges to the fixed structure of switch **240**. Upper electrode **266** is capable of establishing contact with a fixed lower electrode **250** when membrane **268** flexes downward in response to pressure applied by a texture protrusion or ridge. Switch **240** differs from the switch **40** described above in that the upper electrode of switch **240** is not anchored around its edges to the fixed structure of the switch. The stiffness properties of membrane **252** are determined primarily by the properties of the protective, insulative part **268**, rather than by the properties of upper electrode **266**.

[0065]   Fig. 9-B shows a side sectional view of a membrane switch **340** according to another alternative embodiment of the present invention. Switch **340** is shown in its quiescent, open state. Switch **340** is part of a larger two-dimensional array, and is connected to row and column leads (not shown) as described above. Switch **340** includes a membrane structure (membrane) **352** including an upper electrode membrane **366** anchored around its edges to the fixed structure of the switch, and an insulative, protective, coupling button **368** disposed above upper electrode **366**. Button **368** extends above the fixed surfaces of switch **340**, so as to couple the downward pressure applied by texture ridges to upper electrode **366**. The downward pressure results in contact between the movable upper electrode **366** and a fixed lower electrode **350**. Switch **340** differs from the switch **40**

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described above in that the button **368** is not anchored around its edges to the fixed part of switch **340**.

[0066]   Fig. **9-C** shows a side sectional view of a membrane switch **440** according to yet another alternative embodiment of the present invention. Switch **440** is shown in its quiescent, closed state. Switch **440** is part of a larger two-dimensional array, and is connected to row and column leads (not shown) as described above. Switch **440** includes a fixed, annular upper electrode **466** facing downward into a first generally annular cavity **454a**. Upper electrode **466** is rigidly coupled to a base **462** of switch **440**, and does not move substantially during the operation of switch **440**. Upper electrode **466** is disposed on the bottom side of a cantilevered, annular support **480** which is rigidly coupled to base **462**. Upper electrode **466** extends around a vertical aperture **496** defined in the center of support **480**.

[0067]   A flexible membrane structure **452** comprises a flexible lower electrode membrane **450** anchored around its edges to base **462**. The middle part of membrane **450** extends upward from base **462**, and is separated from base **462** by a disk-shaped second cavity **454b**. A coupling button **468** is disposed above the middle part of lower electrode **450**, through vertical aperture **496**. Coupling button **468** extends above the fixed surfaces of switch **440**, so as to couple applied downward pressure to lower electrode membrane **450**. A thin, flexible sheet **498** is disposed over the entire switch array, above the corresponding coupling buttons of all the switches in the array. Flexible sheet **498** serves to keep particulate matter away from the contact surface between the fixed upper electrode **466** and the movable lower electrode **450**.

[0068]   Switch **440** is closed in its quiescent state, when no pressure or texture is applied. In the quiescent state, upper electrode **466** is in electrical contact with lower electrode **450**. When a texture ridge or protrusion applies downward pressure to lower electrode **450** through sheet **498** and coupling button **468**, lower electrode **450** flexes downward and breaks its electrical contact to upper electrode **466**. Switch **440** is then open. When the applied pressure is removed, lower electrode **450** returns to its quiescent state and switch **440** becomes closed again.

[0069]   The structure described with reference to Fig. **9-C** may be modified in a manner similar to the one described above with reference to Fig. **9-A**. An insulative lower membrane may be used instead of a conductive one, and a conductive lower electrode is disposed onto the top surface of the insulative membrane.

[0070]   The use of the suspended-membrane switch designs described above allows enhanced reliability and relative insensitivity to the amount of pressure applied by the individual. The flexible membrane is capable of closing each switch in response to relatively light pressure applied by a user. Since the lower and upper electrodes are spaced closely apart relative to their in-plane extents, excessive application of force to the upper electrode does not generally cause fracture of the membrane. The switch and associated passive resistor design minimizes the need to use transistors to address the different cells using expensive CMOS processes. The switch is relatively insensitive to electrostatic discharge or other voltage spikes that would otherwise damage silicon-based sensors.

[0071]   The power consumption of the sensor device is relatively low, since a relatively small amount of current is used to test for the state of each electrical circuit when a

finger or texture is placed on the sensor. Additionally, the sensor is on only when a fingerprint is being acquired, which reduces the drain on the energy source used for polling the sensor. In its quiescent state, the sensor draws no current. Low power consumption is particularly useful in portable devices such as cellular phones and laptop computers.

[0072]   The sensor is relatively insensitive to the choice of materials, and thus can be made relatively robust through the use of materials having relatively high corrosion and abrasion resistance. The device can be made relatively inexpensively, since its fabrication does not require expensive processing of silicon wafers. The relative ease of processing allows for the fabrication process to be applied to large area substrates, yielding more sensors per processed wafer and decreased manufacturing costs.

[0073]   The use of a membrane allows eliminating the lateral motion of the upper electrode relative to the lower electrode. The membrane design facilitates the sealing of the chamber containing the contact surface of the switch, thus preventing external particles from contaminating the contact surface and blocking the switch in an open or closed state. Such particles could in principle contaminate the contact surface during normal operation of the sensor, or during manufacturing steps used to fabricate the sensor. The chamber sealing can be appropriately tailored to allow the passage of air in and out of the chamber while preventing the entry of contaminants. It is thought that the preferred manufacturing process and structure described above allows keeping out contaminants that are larger than on the order of hundreds or thousands of Ångstroms. Allowing the pressure inside the switch chambers to become equal to the pressure

outside the switches reduces the dependence of the switch operation on environmental pressure.

[0074]   The individual membrane sealing reduces the need for a global cover sheet applied over all the switches for mechanical protection. A thick or inflexible cover sheet can lead to cross-talk between adjacent switches, as switches disposed under valleys are pressed downward by the downward motion of the cover sheet pressed down by adjacent ridges. Providing inter-switch tunnels allows the pressure within different switch chambers to equalize. Equalizing the pressures in different switch chambers leads to reduced variability in the force required to close different switches. A flexible, global cover sheet applied over all the switches can be used in a sensor according to alternative embodiments of the present invention.

[0075]   The profile and relatively compact size of the flexible membrane structure allows the use of thick, hard field regions between adjacent membrane structures. The field regions protect the membrane structures from high impact forces and lateral shear forces caused by scratching, aggressive wiping, rubbing or other forces.

[0076]   A global sealed vent may be used at the end of each row or column of switches, in order to facilitate the equalization of pressure between the interior chambers of multiple sensor switches and the external environment. Such a global vent may include an aperture, facing upward, that communicates with one or more interswitch tunnel(s) of the sensor. The aperture can be sealed by a structure such as a polymer film, so as to prevent the entry of particulate contaminants into the interswitch tunnels.

[0077]   In alternative embodiments, a substrate made of a insulator such as a plastic may be employed to support the switch array. Various conductors can be deposited on the insulator, and insulative sheets may be laminated onto the substrate to provide desired insulation between the conductors.

[0078]   In an alternative embodiment, the quiescent state of each state is closed rather than open. A flexible membrane can then include a movable lower electrode of the switch disposed on the upper surface of a membrane. The membrane is separated from the base by a cavity allowing downward flexure of the membrane into the cavity. A fixed upper electrode of the switch is disposed along a protrusion which forms part of the base or is rigidly attached to the base. The upper electrode faces downward. In the closed quiescent state, the fixed and movable electrodes are in contact along an annular region around the cavity. When the membrane is pressed down by an applied ridge, the flexure of the membrane causes the lower electrode to move downward so as to break the contact between the fixed and movable electrodes.

[0079]   It will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. For example, the edges of the upper electrode need not be anchored to the fixed switch structure.   An unanchored upper electrode can be stacked underneath another membrane layer which is anchored around the edges to the fixed switch structure. Devices as described above can be used in robotic control applications, on the tips of robotic arms, for sensing textures of objects rather than skin. A button disposed on each flexible membrane structure can extend above the other structures of the sensor, in order to facilitate the coupling of texture ridges to the flexible membranes.   The

switch chambers can be sealed to be air- or vacuum-tight, in order to maintain a vacuum or given amount of air within the chambers.   Inter-chamber tunnels can be provided along both orthogonal directions (row and column) of the sensor, as well as

5   along other directions.   The vents used for removing the sacrificial layers can be positioned in various places, such as above an inter-chamber tunnel.   Various materials, layer thicknesses and other structural dimensions are given for illustrative purposes.   It is understood that other dimensions

10   and materials can be suitable for use with the present invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.